# Probing Topcolor-Assisted Technicolor from Top-Charm Associated Production at LHC

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We propose to probe the topcolor-assisted technicolor (TC2) model from the top-charm associated productions at the LHC, which are highly suppressed in the Standard Model. Due to the flavor-changing couplings of the top quark with the scalars (top-pions and top-Higgs) in TC2 model, the top-charm associated productions can occur via both the $s$-channel and $t$-channel parton processes by exchanging a scalar field at the LHC. We examined these processes through Monte Carlo simulation and found that they can reach the observable level at the LHC in quite a large part of the parameter space of the TC2 model.

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The fancy idea of technicolor (TC) provides a possible mechanism of breaking the electroweak symmetry dynamically. However, it is hard for technicolor to generate the fermion masses, especially the heavy top quark mass. As a realistic TC model, the topcolor-assisted technicolor (TC2) model [1] combines technicolor with topcolor, with the former mainly responsible for electroweak symmetry breaking and the latter for generating a major part of top quark mass. This model is one of the promising candidates of new physics, awaiting to be tested at the upcoming CERN Large Hadron Collider (LHC).

As shown in numerous previous studies, the top quark processes are sensitive to new physics [2]. In some new physics models like supersymmetry, there may emerge some new production and decay mechanisms for the top quark at hadron colliders [3–5]. The study of these new mechanisms will help to reveal the new physics effects. It is noticeable that the TC2 model may have richer top-quark phenomenology than other new physics models since it treats the top quark differently from other quarks to single out top quark for condensation [1]. In fact, the top-color interaction is flavor non-universal and consequently may induce new large flavor-changing (FC) interactions [6,7]. One kind of such FC interactions occur between quarks and the top-pion, the pseudo-goldstone boson predicted by TC2 model with mass of a few hundred GeV, which are given by [1,6]

$$\mathcal{L} = \frac{m_t}{\sqrt{2}F_t}\frac{\sqrt{v^2-F_t^2}}{v}\Big[iK_{UR}^{tt}K_{UL}^{tt*}\bar{t}_L t_R \pi_t^0 + \sqrt{2}K_{UR}^{tt*}K_{DL}^{bb}\bar{t}_R b_L \pi_t^+ + iK_{UR}^{tc}K_{UL}^{tt*}\bar{t}_L c_R \pi_t^0 + \sqrt{2}K_{UR}^{tc*}K_{DL}^{bb}\bar{c}_R b_L \pi_t^+ + h.c.\Big], \quad (1)$$

where $v \simeq 174$ GeV, $F_t \simeq 50$ GeV is the top-pion decay constant and the factor $\sqrt{v^2-F_t^2}/v$ reflects the effect of the mixing between the top-pions and the would-be goldstone bosons [8]. $K_{UL}$, $K_{DL}$ and $K_{UR}$ are the rotation matrices that transform the weak eigenstates of left-handed up-type, down-type and right-handed up-type quarks to the mass eigenstates, respectively. As pointed out in [6], the transition between $t_R$ and $c_R$, $K_{UR}^{tc}$, can be naturally around $10\% \sim 30\%$ without conflict with low energy experimental data and $K$s can be parameterized as follows:

$$K_{UL}^{tt} = K_{DL}^{bb} = 1, \qquad K_{DR}^{tt} = 1-\epsilon,$$
$$K_{UR}^{tc} = \sqrt{1-{K_{UR}^{tt}}^2-{K_{UR}^{tu}}^2} \le \sqrt{2\epsilon-\epsilon^2}, \quad (2)$$

with $\epsilon$ representing the fraction of top quark mass generated from TC interactions. Throughout this paper, we fix $K_{UR}^{tc} = \sqrt{2\epsilon-\epsilon^2}$ and treat $\epsilon$ as an input parameter in the range $0 \sim 0.1$. TC2 model also predicts a CP-even scalar $h_t$ called top-Higgs [7]. Its couplings to quarks are similar to that of the neutral top-pion except that the neutral top-pion is CP-odd.

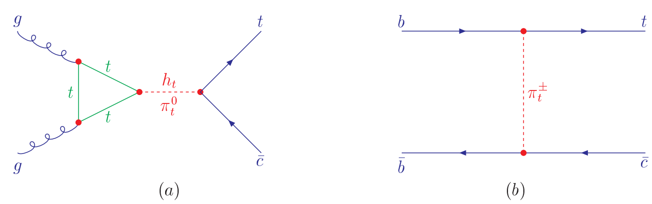


FIG. 1. Feynman diagrams contributing to $t\bar{c}$ associated production in TC2 model.

The above large Yukawa couplings will induce the top-charm associated production $pp \to t\bar{c} + X$ through both the $s$-channel $gg \to \pi_t^0, h_t \to t\bar{c}$, as shown in Fig.1(a), and the $t$-channel $bb \to t\bar{c}$ by exchanging a $\pi_t^+$, as shown in Fig.1(b). Compared to the $t\bar{b}$ productions, which is also sensitive to TC2 [6], the $t\bar{c}$ productions are highly suppressed in the SM and thus its observation would be a robust evidence of new physics.

The $t\bar{c}$ production through the $s$-channel $gg \to h_t \to t\bar{c}$ has been briefly studied in the literature [7]. But a detailed Monte Carlo study of its observability, with

the consideration of the SM backgrouds, is still lacking. Given the great importance of the LHC phenomenology, such a study of observability is absolutely necessary. Furthermore, the $t\bar{c}$ production via the $t$-channel $bb \to t\bar{c}$, which is more important when the top-pion is heavy, has not been studied before. In this work we will give a comparative study of both processes. We will not only study the production rates, but also perform a Monte Carlo simulation to show explicitly the observability at the LHC. Our result shows that both the $s$-channel and $t$-channel processes can reach the observable level at the LHC in quite a large part of the parameter space. Therefore, looking for the top-charm associated productions at the LHC will serve as an important probe for the TC2 model.

The spin- and color-averaged amplitudes of the $s$-channel and $t$-channel processes are given by

$$|\mathcal{M}_s^{\pi_t^0}|^2 = \frac{1}{64}\left(\frac{m_t^2}{2F_t^2}\frac{v^2-F_t^2}{v^2}\frac{\alpha_s}{\pi}\right)^2(2\epsilon-\epsilon^2)(1-\epsilon)^2 \times\left|c_1\left(\frac{\hat{s}}{m_t^2}\right)\right|^2\frac{m_t^2(\hat{s}-m_t^2)}{(\hat{s}-m_{\pi^0}^2)^2+m_{\pi^0}^2\Gamma_{\pi_t^0}^2}, \quad (3)$$

$$|\mathcal{M}_s^{h_t}|^2 = \frac{1}{64}\left(\frac{m_t^2}{2F_t^2}\frac{v^2-F_t^2}{v^2}\frac{\alpha_s}{\pi}\right)^2(2\epsilon-\epsilon^2)(1-\epsilon)^2 \times\left|c_2\left(\frac{\hat{s}}{m_t^2}\right)\right|^2\frac{m_t^2(\hat{s}-m_t^2)}{(\hat{s}-m_{h_t}^2)^2+m_{h_t}^2\Gamma_{h_t}^2}, \quad (4)$$

$$|\mathcal{M}_t^{\pi_t^+}|^2 = \left(\frac{m_t^2}{2F_t^2}\frac{v^2-F_t^2}{v^2}\right)^2(2\epsilon-\epsilon^2)(1-\epsilon)^2 \times\frac{\hat{t}(\hat{t}-m_t^2)}{(\hat{t}-m_{\pi^+}^2)^2}, \quad (5)$$

where $\alpha_s = g_s^2/(4\pi)$ with $g_s$ denoting strong coupling constant, $\hat{s}$ and $\hat{t}$ are patron level Mandelstam variables. $\Gamma_{\pi_t^0}$ ($\Gamma_{h_t}$) is the width of neutral top-pion (top-higgs) which can be calculated by considering all its decay modes. $c_{1,2}(R)$ are loop functions defined by $c_1(R) = \int_0^1 \mathrm{d}x\frac{\ln(1-Rx(1-x))}{x}$ and $c_2(R) = -2+(1-\frac{4}{R})c_1(R)$. Note there is no interference between $M_s^{\pi_t^0}$ and $M_s^{h_t}$ due to different CP property of $\pi_t^0$ and $h_t$. In our numerical calculation, we use the CTEQ5L parton distribution functions [9] with $Q = \sqrt{\hat{s}}/2$.

In Fig.2 we plotted the two-body $t\bar{c}$ production cross section versus corresponding scalar mass for both the $s$-channel and $t$-channel processes. The charge conjugate production channel, i.e., the $\bar{t}c$ production, is also included in our analysis throughout this paper.

We see from Fig.2 that for the $t$-channel process the production rate drops monotonously with the increase of the charged top-pion mass. For the $s$-channel processes the production rates are maximum when the neutral scalars lie in the range of $m_t + m_c \lesssim m_{\pi_t^0,h_t} \lesssim 2m_t$. The reason is that in this range, $t\bar{c}$ is the dominant decay mode of the neutral scalars. Comparing the rates of $s$- and $t$-channel productions, one sees that for a common scalar mass the $s$-channel rate is higher than the $t$-channel rate only in the range from $m_t$ to 400 GeV. From this figure one can also see that the cross section of $pp \to \pi_t^0 \to t\bar{c}$ is at least a couple of times larger than that of $pp \to h_t \to t\bar{c}$ for $m_{\pi_t^0} = m_{h_t}$.

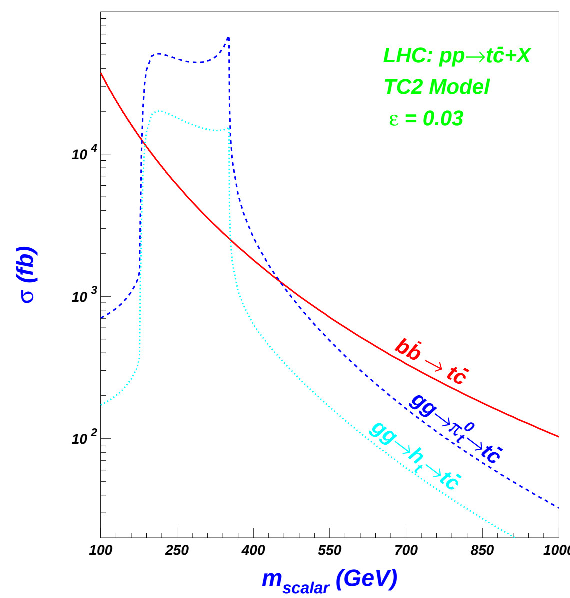


FIG. 2. Cross sections of top-charm associated production as a function of corresponding scalar mass for different parton processes at the LHC.

Under the assumption that the top quark decays via the normal weak interactions to $Wb$, the final state of $t\bar{c}$ production is $Wb\bar{c}$. We look for events with the leptonic decay of the $W$, $W \to \ell\bar{\nu}$ ($\ell = e$ or $\mu$) and thus the signature of $t\bar{c}$ production is an energetic charged lepton, one $b$-quark jet, one light $c$-quark jet, plus missing $E_T$ from the neutrino. The potential SM backgrounds are the single top productions, top pair ($t\bar{t}$) productions, and $Wb\bar{b}$, $Wc\bar{c}$, $Wcj$ and $Wjj$ productions. These backgrounds have been studied extensively in [11]. In order to use the background results in [11], in our analysis we applied the same selection cuts as in [11].

First, we assumed silicon vertex tagging of the $b$-quark jet with 60% efficiency and the probability of 0.5% (15%) for a light quark ($c$-quark) jet to be mis-identified as a $b$-jet, which can reduce the background $Wjj$ efficiently. We required the reconstructed top quark mass $M(bW)$ to lie within the mass range $|M(bW) - m_t| < 20$ GeV, which can reduce all the non-top backgrounds efficiently.

To simulate the detector acceptance, we made a series of basic cuts on the transverse momentum ($p_T$), the pseudo-rapidity ($\eta$), and the separation in the azimuthal angle-pseudo-rapidity plane ( $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$ ) between a jet and a lepton or between two jets. These

cuts are chosen to be

$$p_T^\ell,\ p_T^j,\ p_T^{\rm miss} \geq 20\ {\rm GeV}\ , \tag{6}$$

$$|\eta_\ell| \leq 2.5,\ |\eta_j| \leq 4,\ |\eta_b| \leq 2\ , \tag{7}$$

$$\Delta R_{jj},\ \Delta R_{j\ell} \geq 0.7\ . \tag{8}$$

Further simulation of detector effects is made by assuming a Gaussian smearing of the energy of the final state particles, given by $\Delta E/E = 30\%/\sqrt{E} \oplus 1\%$ for leptons and $\Delta E/E = 80\%/\sqrt{E} \oplus 5\%$ for hadrons, where $\oplus$ indicates that the energy dependent and independent terms are added in quadrature and $E$ is in GeV.

Under the above cuts the total cross section of backgrounds is 16839 fb [11], of which 7159 fb is from single top productions, 2770 fb from $t\bar{t}$ productions, and 5070 fb, 1460 fb, 230 fb and 150 fb from $Wcj$, $Wjj$, $Wb\bar{b}$, $Wc\bar{c}$ productions, respectively.

A few remarks are due regarding our analysis:

(1) The main kinematic difference between the $s$- and $t$-channel processes is that for the former the signal has a peak in the top-charm invariant mass distribution and this feature might be used to effectively reduce background [7]. In our analysis, we ignored this difference and adopt the same strategy to probe the top-charm signal. The reason is twofold. One is that without any information of $m_{\pi^0}$ and $m_{h_t}$, we do not know where the peak lies at. The other is, due to strong interaction of the neutral scalars with quarks, their widths are of several hundred GeV for $m_{\pi^0,h_t} > 2m_t$ and as a result, the peak is highly smeared.

(2) The two jets in the signal are $b\bar{c}$ (or $\bar{b}c$). Since the $c$-quark jet could be mis-identified as a $b$-jet with a probability of 15%, the efficiency of tagging one $b$-jet from $b\bar{c}$ (or $\bar{b}c$) should be slightly higher than 60%. In our analysis we conservatively assumed the tagging efficiency of 60%.

(3) For the same reason stated above, we could possibly require to tag two $b$-jets for the signal. Compared with tagging only one $b$-jet, this will further reduce the signal rate by a factor of 15% while suppress the $Wjj$ and $Wcj$ backgrounds by a factor of 0.5%. However, the large backgrounds of top quark productions cannot be relatively suppressed because they contain two $b$-jets in their final states. As a result, the total background is reduced only by a factor of 37%. So this strategy of tagging two $b$-jets does no better.

The observability of the $t\bar{c}$ productions through $gg \to \pi_t^0 \to t\bar{c}$ and $b\bar{b} \to t\bar{c}$ are shown in Figs. 3 and 4 for the LHC with $L = 100\ {\rm fb}^{-1}$. Throughout our analysis we restrict the value of the parameter $\epsilon$ in the range of $0.001 \sim 0.1$.

We see from Figs. 3 and 4 that for both processes the observable parameter region is quite large. For the $s$-channel process the region $m_t + m_c \lesssim m_{\pi_t^0} \lesssim 2m_t$ is observable for any $\epsilon$ value in the range of $0.001 \sim 0.1$. The reason for this is already elucidated in the discussions for Fig.2. Outside the region the signal is observable only for enough large $\epsilon$ value. But given $0.001 \leq \epsilon \leq 0.1$ , the signal is observable for $m_{\pi_t^0} \lesssim 550$ GeV. In case of nonobservation, the $2\sigma$ lower limit on $m_{\pi_t^0}$ is about 600 GeV.

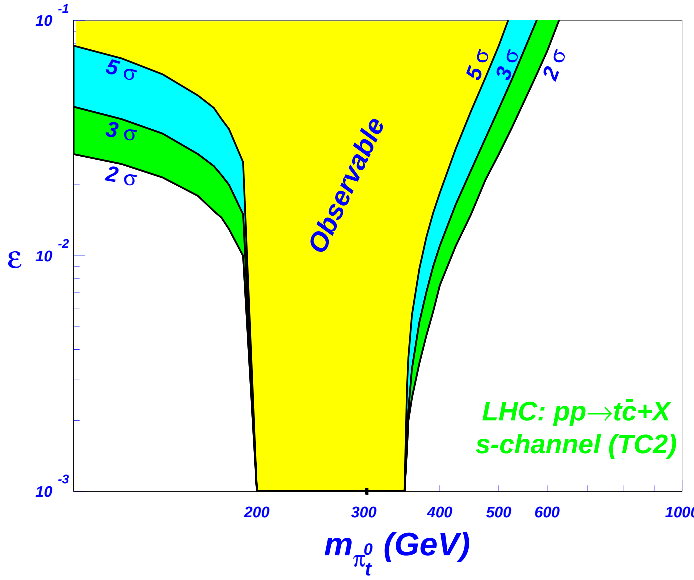


FIG. 3. Observable region in the plane $(m_{\pi_t^0}, \epsilon)$ for the production $pp \to t\bar{c} + X$ through $s$-channel parton process $gg \to \pi_t^0 \to t\bar{c}$ at the LHC with $L = 100\ {\rm fb}^{-1}$.

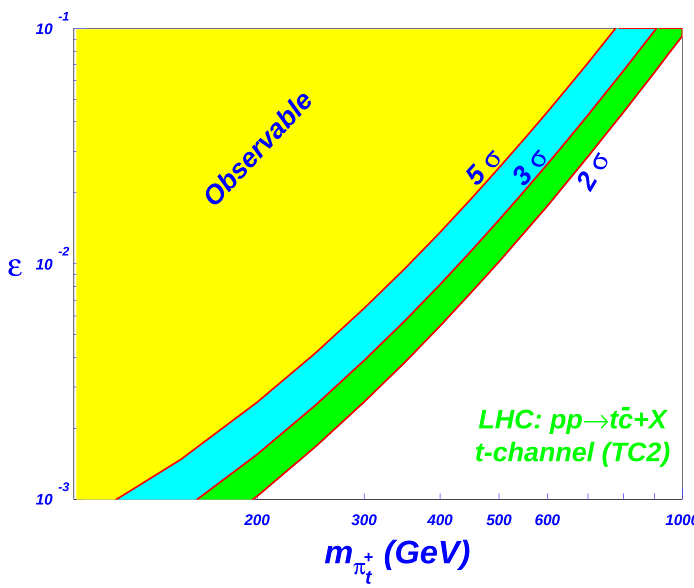


FIG. 4. Same as Fif.3, but for the production $pp \to t\bar{c} + X$ through $t$-channel $b\bar{b} \to t\bar{c}$.

The $t$-channel process exhibits a different feature from the $s$-channel process, which can be inferred from the behavior of its two-body $t\bar{c}$ production rate shown in Fig.2. The observable region of the parameter space shrinks monotonously with the increase of the charged top-pion mass. But for a relatively high $\epsilon$ value in the range of

$0.001 \sim 0.1$, the signal is observable up to $m_{\pi_t^+} \simeq 800$ GeV. This value is much larger than the constraint from $R_b$ [12], *i.e.* $m_{\pi_t^+} \gtrsim 250$ GeV. In case of nonobservation, the $2\sigma$ lower limit on $m_{\pi_t^+}$ can reach 1 TeV.

We did not show the observable region in the plane ($h_t$, $\epsilon$) for the s-channel process $gg \to h_t \to t\bar{c}$ because it is similar to Fig.3. The only difference is if $\epsilon \leq 0.1$, the signal is observable at $3\sigma$ level for $h_t \lesssim 480$ GeV and unobservable at $2\sigma$ level for $h_t \gtrsim 530$ GeV.

In our analysis of neutral scalar production, we did not choose $t\bar{t}$ as the signal of the new physics for $m_{\pi^0}, m_{h_t} > 2m_t$. The reason is the effect of these scalars on the cross section of $t\bar{t}$ is small, resulting in a contribution of the order of $\sigma(t\bar{t})_{TC2}/\sigma(t\bar{t})_{SM} = 10^{-2} \sim 10^{-3}$ at the LHC.

In some extensions of the SM, such as the generic two-Higgs doublet models with tree level FC scalar interactions [13], both $s$- and $t$-channel top-charm associated productions can also occur via exchanging neutral and charged Higgs bosons, respectively. However, although the corresponding cross sections are large, they are at least one order of magnitude smaller than those of TC2 for a common mass of Higgs bosons and top-pions [6]. The reason is that TC2 model predicts a large Yukawa coupling $\frac{m_t}{2F_t} \simeq 2.5$ and a possible large FC coefficient $K^{tc}_{UR}$ (see Eq.(1)).

The interactions between the scalars and quarks can also induce large neutral flavor changing gauge interaction, such as the coupling $t\bar{c}g$ [14]. Since it is not easy to observe top rare decay $t \to cg$ at hadron collider [15], such a coupling may be well tested via single top production, $cg \to t$, at the LHC. This process was extensively studied in effective Lagrangian approach [16] with the conclusion that for LHC with 100 $\text{fb}^{-1}$ the discovery limit on the effective interaction coefficient $\kappa_c/\Lambda$ is 0.0048 $\text{TeV}^{-1}$ at $3\sigma$ level, or alternatively, new physics contribution to the cross section $pp \to t^* \to b\bar{l}_e v_e$ must be larger than 40 fb. We examined this process in TC2 model and found that for $\epsilon \leq 0.1$ only when $m_{h_t} \leq 400$ GeV and $m_{\pi^+,\pi^0} \leq 350$ GeV can such single top events be observable. Obviously, the observable region is smaller than that from top-charm associated production.

TC2 model also predicts some new top-quark decay modes, such as $t \to b\bar{b}c$ via exchanging a $\pi_t^+$ and $t \to cWW$ via an intermediate $h_t$. Among these new decay modes, $t \to b\bar{b}c$ is dominant for a not heavy charged top-pion. For example, for $\epsilon = 0.1$ and $m_{\pi^+} = 250$ GeV, the ratio $\Gamma(t \to b\bar{b}c)/\Gamma(t \to bW)$ can reach $9 \times 10^{-3}$, which maybe not accessible at the LHC due to the SM backgrounds [17]. For the decay mode $t \to cWW$ [18], it drop quickly with the increase of $m_{h_t}$ and for $m_{h_t} > 250$ GeV the ratio $\Gamma(t \to WW)/\Gamma(t \to bW)$ is of $10^{-7}$. As a result, such a decay mode cannot put severe bounds on TC2 parameter.

So we conclude the top-charm associated productions at the LHC are a powerful probe for the TC2 model. The LHC can either observe the productions or set stringent bounds on the parameters of the TC2 model.

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